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OTS: 60-31,210

JPRS: 3351

1 June 1960

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- USSR -

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Distributed by:

OFFICE OF TECHNICAL SERVICES
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WASHINGTON 25, D. C.
[redacted]

U. S. JOINT PUBLICATIONS RESEARCH SERVICE
205 EAST 42ND STREET, SUITE 300
NEW YORK 17, N. Y.

F O R E W O R D

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JPRS: 3351

CSO: 3648-D

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[Following is a translation of an article by G. A. Gurzadyan in Doklady Akademii nauk SSSR (Bulletin of the Academy of Sciences USSR), Vol. 130, No. 2, January 1960, Moscow, pages 287-289.]

The following was presented by academician V. A. Ambartsumyan on 11 September 1959.

Let us assume synchrotronic radiation (bremsstrahlung of relativistic electrons in a magnetic field) is produced in the atmosphere or in a limited volume of the atmosphere of a star. Let us assume further that the density of the synchrotronic radiation in the region of short waves, shorter than 912 Angstrom units (L_c-radiation), is markedly greater than the density obtained by Planck's formula at the temperature of the star T_*. Then one may consider that ionization of hydrogen atoms in the medium is caused wholly by the density of the synchrotronic radiation. Inasmuch as the occurrence of forbidden lines in it is excluded, the electron temperature of this medium will obviously be determined by the residual energy of the electrons detached in the photoionization of hydrogen atoms under the influence of synchrotronic L_c-radiation.

In this article the problem of determining the electron temperature of the medium will be examined with the following assumptions: a) that free electrons are formed by photoionization of hydrogen atoms under the influence of synchrotronic short-wave radiation generated in the given volume of the atmosphere of a star; b) that the electrons lose their energy by recombination processes connected with hydrogen; c) that a Maxwell distribution of velocities is established between electrons.

The following two equilibrium conditions constitute initial conditions in solving this problem: a) the steady-state condition - the number of atoms entering the continuum during photoionization per unit of time should be equal to the number of atoms leaving the continuum; b) the condition of radiant equilibrium - the quantity of energy spent in the photoionization of the hydrogen atoms should be equal to the quantity of energy radiated during recombination.

Let us also assume that photoionization occurs only at the ground state. This assumption can be considered acceptable if we bear in mind the extremely small degree of excitation of hydrogen atoms under the conditions prevailing in stellar atmospheres.

Recombinations of free electrons occur at all levels and we shall take them into consideration. As the role of free-free transitions is insignificant, we shall neglect them.

If the energy spectrum of the relativistic electrons is continuous and has the form

$$N_e = K^{-\gamma} ,$$

then the radiation density at frequency ν generated by these electrons when decelerated in a magnetic field can be represented in the following form:

$$p_\nu = \text{const} \cdot \nu^{(1-\gamma)/2} . \tag{1}$$

Using n_1 to designate the number of hydrogen atoms in the ground state per unit volume and $k_{1\nu}$ the coefficient of continuous absorption per atom, we shall have the following expression for the number of ionizing events per unit of time:

$$n_1 \int_{\nu_0}^{\infty} k_{1\nu} \frac{p_\nu c}{h\nu} d\nu , \tag{2}$$

where ν_0 is the frequency of ionization.

For the number of recombinations at all levels we have (refer, for example, to [1]

$$4\pi n^+ n_e \left(\frac{m_e}{2\pi kT_e}\right)^{3/2} \sum_{i=1}^{\infty} \int_0^{\infty} \beta_i(T_e) e^{-m_e v^2/2kT_e} v^3 dv \tag{3}$$

when n^+ and n_e are the number of hydrogen ions and free electrons per unit volume; T_e is the electron temperature of the medium; and $\beta_i(T_e)$ is the effective recombination cross section.

Applying the steady-state conditions, we obtain

$$n_1 \int_{\nu_0}^{\infty} k_{1\nu} \frac{p_\nu c}{h\nu} d\nu = 4\pi n^+ n_e \left(\frac{m_e}{2\pi kT_e}\right)^{3/2} \sum_{i=1}^{\infty} \int_0^{\infty} \beta_i(T_e) e^{-m_e v^2/2kT_e} v^3 \, dv . \tag{4}$$

To write the condition of radiant equilibrium, it is necessary to calculate the energy absorbed in photoionization and the energy radiated in recombination and to equate them. We obtain

$$n_1 \int_{\nu_0}^{\infty} k_{1\nu}\, p_\nu\, c\, d\nu = 4\pi n^+ n_e \left(\frac{m_e}{2\pi k T_e}\right)^{3/2} \sum_{i=1}^{\infty} \int_0^{\infty} \beta_i(T_e) h\nu\, e^{-m_e v^2/2kT_e}\, v^3\, d \quad . \tag{5}$$

The function $\beta_i(T_e)$, which is included in (4) and (5), has the form

$$\beta_i(T_e) \sim k_{1\nu} \frac{i^2 \nu^2}{v^2} \quad . \tag{6}$$

In writing the expressions for coefficients of absorption $k_{1\nu}$ and $K_{i\nu}$, we also take negative absorption into consideration. We then obtain

$$k_{1\nu} \sim \frac{1}{\nu^3}\left(1 - e^{-h\nu/kT_e}\right); \quad k_{i\nu} \sim \frac{1}{\nu^3\, i^5}\left(1 - e^{-h\nu/kT_e}\right) . \tag{7}$$

Taking (1), (6), and (7) into account, we find from (4) and (5) after substituting the quantity $h\nu - h\nu_i$ into them in place of $m_e v^2$:

$$\frac{\int_{x_0}^{\infty} x^{-(7+\gamma)/2}\left(1 - e^{-x}\right) dx}{\int_{x_0}^{\infty} x^{-(5+\gamma)/2}\left(1 - e^{-x}\right) dx} = \frac{\sum_{i=1}^{\infty} \frac{e^{x_i}}{i^3}\left[\int_{x_i}^{\infty} \frac{e^{-x}}{x}\, dx - \int_{2x_i}^{\infty} \frac{e^{-x}}{x}\, dx\right]}{\sum_{i=1}^{\infty} \frac{1}{i^3}\left(1 - \frac{1}{2} e^{-x_i}\right)} \tag{8}$$

where $x_0 = h\nu_0/kT_e$; $x_i = h\nu_i/kT_e$; and ν_i is the frequency of ionization of the i-th state.

In equation (8) the only unknown is the electron temperature T_e, which is uniquely determined. For this x_0, at a given value of γ, is first determined from (8), then T_e is calculated from the relationship

$$T_e = \frac{h\nu_0}{kx_0} \tag{9}$$

An analysis of the formulas written here shows that the electron temperature of the medium under synchrotronic radiation has a weak dependence on the spectrum of relativistic electrons γ, therefore it is determined wholly by the mechanism of luminescence of the medium.

Calculations yielded values of $T_e = 110,000^\circ$ when $\gamma = 3$; and $T_e = 100,000^\circ$ when $\gamma = 5$.

Thus the theoretical electron temperature of the atmosphere (or part of the atmosphere) of a star where synchrotronic radiation is generated is very high, and is on an order higher than the electron temperature of gas clouds. It is interesting to note that if the radiation of the photospheric layers of a star were represented by Planck's law, the temperature of this star, with the previously given assumptions, would have to be on the order of $200,000^\circ$ to permit an electron temperature in its atmosphere on the order of $100,000^\circ$.

Since the residual energy of electrons is sufficiently high after photoionization of hydrogen, it can be spent partially in the excitation and the ionization of hydrogen atoms in the ground state by inelastic collisions. This factor of loss of energy of electrons can lead to "cooling" of the medium and, consequently, to some lowering of its electron temperature. In order to achieve a marked "cooling" effect, however, it is essential that the concentration of neutral hydrogen atoms be sufficiently great. Even in this case, however, the residual energy of the free electrons would still correspond to a high electron temperature of the medium, because the excitation and ionization potentials of hydrogen have comparatively high values.

Moreover, cases are possible in which the degree of ionization of the hydrogen in the medium is so high that the actual concentration of neutral hydrogen atoms would be insufficient to absorb the greater part of the residual energy of the free electrons. In this case, the effect of "cooling" by neutral hydrogen would have practically no influence on the high value obtained above of the electron temperature of the medium.

It is possible to attempt to obtain proof of these theoretical conclusions, for example, in certain variable stars. If the phenomenon of flares or brief increases in their brightness is caused by the generation of synchrotronic radiation in some part of their atmospheres, then the widths of the spectral lines--and there are grounds for believing that these lines do occur in precisely those regions of the medium where synchrotronic radiation is generated--should be sufficiently great to correspond to the high value of the electron temperature.

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Submitted 8 September 1959

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